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WEAK SOLAR FIELDS AND THEIR CONNECTION TO THE SOLAR CYCLE*

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Abstract. We discuss the weak solar magnetic fields as studied with the BBSO videomagnetograph (VMG). By weak fields we mean those outside active and unipolar regions. These are found everywhere on the Sun, even where there never have been sunspots. These fields consist of the network and intranetwork (IN) elements. The former move slowly and live a day or more; the latter move rapidly (typically 300 m s^{-1}) and live only hours. To all levels of sensitivity the flux is concentrated in discrete elements, and the background field has not been detected. The smallest detectable elements at present are 10^{16} Mx. The IN elements emerge in bipolar form but appear to flow in a random pattern rather than to the network edges; however, any expanding network element is constrained by geometry to move toward the edges.

Because of the great number and short lifetime of the IN elements the total flux emerging in that form exceeds that emerging in the ER by two orders of magnitude and the flux in sunspots, by a factor 10^4. However, the flux separation is small and there is no contribution to the overall field. In contrast with our earlier results, merging of IN fields is more important than the ephemeral regions as a source of new network elements.

The conjecture that all solar magnetic fields are intrinsically strong is discussed and evidence pro and con presented. For the IN fields the evidence suggests they cannot exceed 100 G. For the network fields there is evidence on either side.

Reconnection and merging of magnetic fields takes place continually in the conditions studied.

Because there is a steady state distribution, the amout of new elements created by merging or emergence must balance that destroyed by reconnection or fission and diffusion of the stronger elements.

The weak solar magnetic fields, a term we apply to all magnetic fields outside the sunspots and plages, must play an important role in the Sun's magnetic cycle. Strong flux is observed to reach the surface in active regions, but sunspots do not move in latitude and the reversal of the polar field appears to result from transport of weaker fields, which thus reform the general field of the Sun. The recent work of DeVore *et al.* (1985) has shown that the evolution of large-scale patterns can indeed be matched by modelling the spread of weak fields in accordance with Leighton's (1964) flux transport model. The fit is not perfect; a meridional flow must be assumed and various diffusion parameters must be used to fit the different cases. A little-noticed requirement of these general field models is that flux be conserved, for there is no provision for loss or gain of flux. The elements of flux are known to be discrete, so for the fields to reach the pole in the same clumped form (as they are observed to do), they either must be immune against breakup or recreated by unknown processes.

This points up our lack of understanding of the weak fields. They are found everywhere on the Sun, including places where there have not been sunspots for years or even ever. Thus, while the general polarity distribution is established by the active regions, the density of poles at any point must result from the equilibrium between local creation and destruction of flux elements. Observations have now established that to

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all levels of present sensitivity the fields occur in small clumps and this equilibrium must occur.

The similarity in scale between the supergranulation flow and the network suggests a relationship, and Simon and Leighton (1964) proposed that the outward flow in the supergranulation sweeps the magnetic fields to the edges and enhances the fields there. This process will work to enhance clumped fields in unipolar regions. In an active region, where large regions of one polarity occur, fields indeed are broken up into the network pattern, but no intensification occurs. But in the quiet Sun, supergranulation flow by itself cannot balance the natural diffusion and decay of magnetic poles. Since there are no magnetic monopoles, magnetic field created inside the supergranules must be (and is) bipolar, so the supergranulation will sweep both positive and negative polarity to cell walls, producing no net concentration of flux. If the new dipoles accidentally came up exactly at the center of the network cells and were separated by the supergranule velocities, all of our network patterns would show fields of one polarity on one side and the other polarity on the other. This is not observed.

The relation between the lifetime of the magnetic network and the supergranulation is unclear. If one maintains the other, then besides the obvious geometric similarity we would see the magnetic patterns rise and fall with the flow patterns. But the supergranulation is uniform all over the Sun, while network lifetimes vary with the original field strength. So the exact association is unclear.

While the magnetic network is easy to observe and single frames of the internetwork (IN) fields have long been obtained at KPNO, the evolution of these fields is a more difficult target. One requires high sensitivity for long periods of time, which means good seing all day and careful guiding and registration. The presence of marginal magnetic structures can be confirmed by their repeated presence on successive frames.

Improvements in the sensitivity of the Big Bear magnetograph have made possible extensive studies of the weak fields. The system, which operates in the $\lambda 6439$ Ca I line, has a pixel size of 0.5 arc sec and has a sensitivity of about 8 G per pixel; the smallest field elements measurable are 2×10^{16} Mx, or 4 G over 1 arc sec square. Because this level can be reached in a 5 min integration (4096 video frames) we can observe the evolution of the intranetwork fields. Our first observations of the weak fields have been reported by Martin *et al.* (1985), Livi *et al.* (1985), and Zirin (1985). Since that time we have obtained many more observations which will be presented at this meeting. The longest runs of good seeing are about 10 hr.

The questions that one wants to answer are, among others, the following:

- Are there large scale flows in the photosphere reflected in the motion of small magnetic elements?
- Can we recognize flows connected with the supergranulation?
- What are the relevant processes in the lifetime of the network elements?
- What is the source and lifetime of the IN elements?
- How do we distinguish between network elements and the IN elements?
- How can we explain field changes that apparently violate Maxwell's laws?

The published data on the weak fields is quite limited. Intensities in the network

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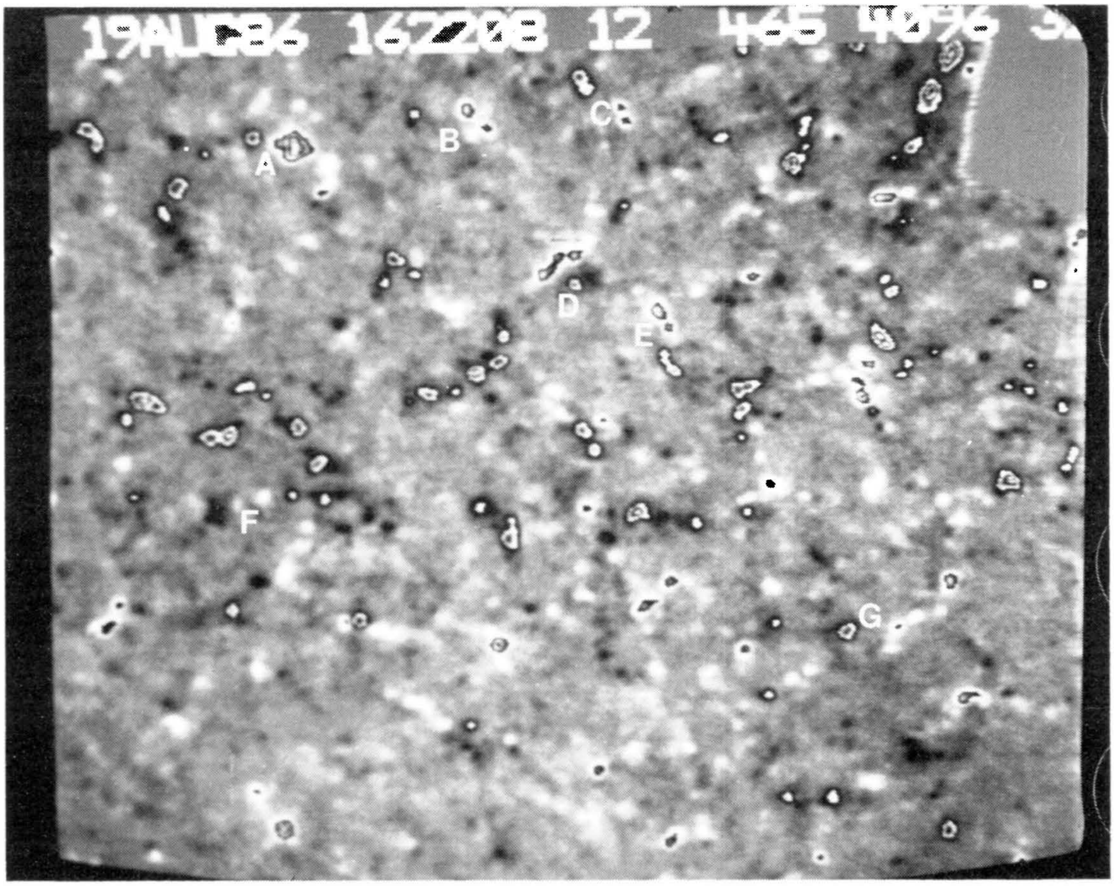

Fig. 1a. Magnetogram on the morning of 19 August 1986.

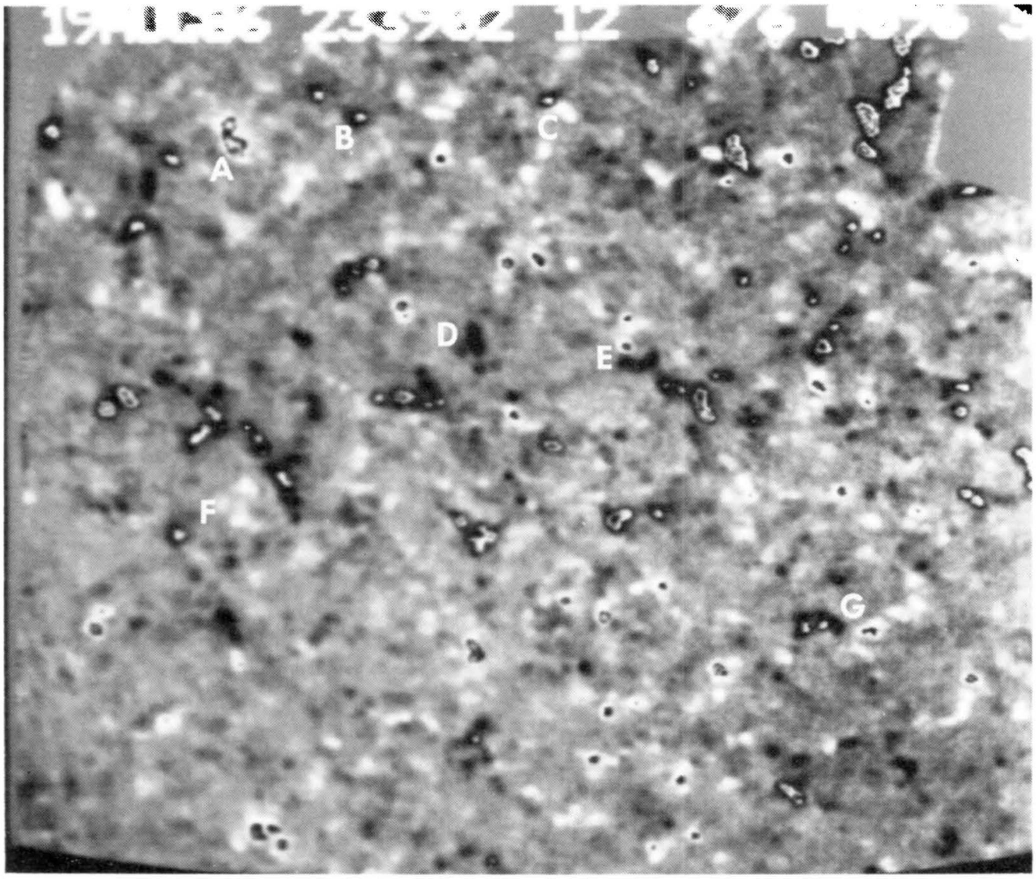

Fig. 1b. Magnetogram near sunset of 19 August, 1986.

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elements have been studied by Tarbell and Title (1977), using the Deslandres (1910) *spectroenregisseur du vitesse* technique. They found that all network elements giving a magnetograph signal above 125 G in fact had field strengths 1000–1500 G. This supported Stenflo's (1973) contention that all the network fields, even the quiet network, are of that strength. These spectrographic observations yielded no evidence on time evolution or on the IN fields. Studies of time variations have yielded contradictory or surprising results. Topka *et al.* 1986 found rapid changes in network sized fields in an hour or two; Wilson (unpublished) found increases in the strength of poles of one sign without corresponding changes in other fields. One feels that either Maxwell's equations do not hold or the data are unreliable.

When one studies a deep VMG movie (Figure 1), one finds an astonishing variety of phenomena. Below the level of the network elements, which are relatively stable, is a rapidly changing pattern of IN fields. Even the relatively stable network elements seem to wax or wane somewhat. As we found in our earlier studies (Zirin, 1985), the velocity of IN elements is on the average 0.35 km s^{-1}, compared to less than 0.1 km s^{-1} for the network. A remarkable exception is those network elements connected by field lines, which may be converging or separating; they move rapidly. Ephemeral regions, driven by buoyancy, move 0.5 km s^{-1}; merging regions, driven by unknown forces, move about 0.3–0.5 km s^{-1}.

To understand the fields in our magnetograms (Figure 1), we must calibrate by measuring the solar rotation in the Doppler mode. This gives for 4096 integrations in the double bandpass mode about 0.6 G/unit/pixel (the image is digitized to 8 bits and each contour wrap is 128 units). However, the single bandpass mode is measured empirically to be twice as sensitive as the double bandpass even though it should be half as sensitive. So we use a calibration of 0.3 G/unit. Thus each wrap contour is about 40 G, and the intensity of the average network element reaches 120 G. The smallest of these are 2 arc sec across, or 2.4×10^{18} Mx. Typically the IN elements show intensities of 10 G, and flux 10^{17} Mx. Since the IN elements are about 5 times more numerous than the network elements and their velocity at least 3 times greater, the flux diffusion by the IN elements may well equal that by the network. But the IN fields are all mixed polarity and their effectiveness in spreading flux may be small.

The flux brought to the surface by the IN activity is considerable. Typically about 5 IN dipoles per hour form in a network cell. Over the entire solar surface this is about 10^{24} Mx per day, or at least two orders of magnitude greater than the ephemeral regions (Harvey *et al.*, 1975). Of course the small-scale nature of these fields means that they do not affect the sign of the field, only its strength.

Can the IN elements be considered an extension of the ER's? More detailed study is necessary, but I do not think they are. The ER's appear immediately as strong elements, and there is a sharp discontinuity in number. A 10 hr observing run in a 4 arc min field will show 3–5 ER's; a single network cell shows about 50 IN dipoles in a day. There is no preferred orientation for IN elements, while Harvey *et al.* (1975) assert that at least part of the ER's follow the Hale–Nicholson law.

As noted above, the lifetime of the network elements is assumed infinite in the models of reversing solar field. In our 1986 study we found that in a sample of 50 network elements about five were completely changed at the end of an eight or nine hour run. The present data give a similar result. This means 10% disappearance in a third of a day or a 30% loss in a day. Since the network is always present, there is a steady state balance between loss and creation of poles. New elements come from ER's and merging of IN elements, and the loss is due to the inverse processes: cancellation with poles of the opposite sign and breakup. In Figure 1 I show two deep magnetograms about 9 hr apart. Elements that change considerably are marked. The following notes pertain to elements marked in the figure:

(A) Dark polarity approaches and disappears into white.
(B) Lower white polarity drifts off.
(C) White polarity merges into black.
(D) White polarity merges into black.
(E) White polarity merges into black.
(F) Dipoles emerge, white flux moves to right.
(G) White and black poles grow through merging.

In the movie we see that other changes take place on smallertime scales; whole dipoles appear and merge. It is entirely possible that inclusion of these phenomena will explain the high diffusion rates.

In some fields such as Figure 1, breakup and creation of new elements are the major factor in network changes; in others, Marsh's (1978) mechanism involving the ER's is important. In Figure 1 we have little ER emergence, mostly splitting and merging. The number and strength of network elements is in equilibrium with the rate of formation of elements by the IN activity, which is strictly random. Marsh's mechanism does not change net flux, but it can refresh fading poles, and ER emergence can of course increase the total flux.

While the quiet network elements change so much from one day to the next that they cannot definitely be identified after 15 hr, the elements of the enhanced network change little, and are usually identifiable for about 48 hr, although they may change.

The IN elements can be used as a measure of flows in the photosphere. They are small enough and last long enough that flows down to 50 millisecond may be seen. In some places these are well marked; one finds a group of IN elements moving in the same direction, and systematic flows of up to 110 m per second may be detected. Other regions show chaotic disarray, and sometimes the flow reverses after eight hours or so. Occasionally we see flow toward elements of the network, and on a statistical basis there may be a net flow. But this is generally masked by random motion of the IN elements. Note that if an IN dipole forms in the center of a cell and separates, the motion will always be toward the edges.

In our previous work (Zirin, 1985) we pointed out that as deeply as we could observe the magnetic field it was always concentrated in individual knots. This is still the case in the 1986 data which is 2 or 3 times more sensitive. It is possible that eventually we will be able to observe field everywhere, but we are far from that at present. Further, in all cases where I could track the origin of IN field, it came up in some sort of dipole. Maxwell's equations are not violated.

There has been a popular view that all elements of the solar magnetic fields have a strength of 1000 G or more which is disguised by filling factor. While this may be true for the stronger network elements, the intensity and flux in the weak intranetwork field is so low that this simply cannot be. The smallest IN elements detectable at present have flux 10^{15} Mx. Because the radiation mean free path of 20 or 30 km probably is the lower size limit, the field strength should not exceed 100 G. In any event the published data supporting strong fields applies only to the network. Another limitation on the network fields is set by the associated continuum brightening. At the limb (Wang and Zirin, 1986) these are resolved into elements not more than 1 arc sec across and up to 30% brighter than the photosphere. If the filling factor was as small as 100, which would be required by the 1000 G fields, then the brightening associated with that magnetic regions would have to be the order of 100 times the intensity of the photosphere, which is most unlikely for a number of reasons. Data for the 12 micron lines (Brault and Noyes, 1983) gives splittings less than a few hundred gauss in the network, which is usually explained by canopy spreading of the field lines; however the bright blue elements near the limb are just as high and quite small.

We have tried some observational tests to shed light on the question of the actual filling factor of the magnetic fields. One test was comparison of magnetograms of different integration length. Magnetograms were taken with 8, 16, 32, 64, 128, and 256 frames. Because these are relatively short only plages cold be seen. Most of the elements measured 2 arc sec, a few measured 1 arc sec. If the magnetic field elements completely filled the pixels, one would expect somewhat greater spread in the fields with the increased exposure, those of 256 frames taking about 15 s. In fact, the measured signal was found to be linear and the size of the observed magnetic elements to be independent of the exposure. This tends to supports the idea of tiny, strong elements with a filling factor. This need not be substantial, since the elements are mostly 2 arc sec across. On our videomagnetograms the field is 280 arc sec or about 2 pixels per arc sec. Another test we have recently made is similar to the observations by Stenflo (1973) which first led to the idea that the fields might be quite strong. By tuning our Zeiss filter we obtained magnetograms in λ6103, 6122, and 6439 within a brief interval. The effects are inconclusive. The measured field intensities are weakest in λ6122 even though it has the highest g-factor. This suggests that either the fields are saturated or the filter profile plays the main role.

On the other hand, the widespread observation of growth and reconnection of the fields means that they are certainly not quantized and must be able to grow and weaken instead of popping in and out like bright lights. Another experiment is to visually examine the flickering live images as they are modulated. The resolution in that case is high because we are not integrating. One sees that the flickering elements are usually larger than granules. This contrast with the size of filigree or continuum bright points, which are clearly smaller. The problem, like the fields, remains unresolved.

One of the most astonishing characteristics of our observations is the continuous merging and apparent reconnection between different magnetic field elements in periods less than an hour. These have been extensively studied by Sara Martin and her co-workers. The exact nature of this merging is not known, but one sees it manifested in different ways. Elements of the same polarity will merge to produce a larger piece of field and elements of opposite polarity will merge to produce a weaker element. The fact that increase or decrease results from the merging proves that we are indeed seeing reconnection. For typical resistivity values and reconnection times of 10^4 s the elements must be smaller than 3 km, although of course instabilities may occur.

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